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A SUSTAINABLE APPROACH FOR IMPROVING AIR QUALITY IN A POULTRY HOUSE.

by

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AN ABSTRACT OF THE THESIS OF

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Maintaining bird health in layer poultry houses is of critical importance for a sustainable production quality. This is directly related to the thermal environment of the laying hens as well as their breathable air quality. This work compares the performance of three passive cooling systems in meeting thermal and IAQ requirements in a poultry house in a semi-arid climate. The first two systems are a direct evaporative cooler (DEC) and a cross flow dew point evaporative cooler (DPIEC) supplying air through a conventional tunnel ventilation that achieves uniform thermal and IAQ conditions. The third system is a DPIEC system supplying air through a localized ventilation system in an effort to reduce air and water consumption. To achieve these objectives, a modular analysis was adopted where mathematical models were developed for the DEC/DPIEC units and the poultry house module conditioned by a tunnel ventilation. Moreover, a 3D CFD model was developed for the compartment conditioned by the localized system. The DEC/DPIEC units were sized and the hourly variation in needed supply fresh air and water was determined for the entirety of the summer season.

Simulation results and a simple economic analysis showed that the DPIEC systems under conventional ventilation were more economically beneficial (4.3%) than the DEC systems, while achieving better compliance with poultry house thermal and IAQ requirements. On the other hand, using localized ventilation instead of conventional ventilation was 10% more economically beneficial, while achieving similar conditions of temperature and IAQ for less supply fresh air and water consumption.

CONTENTS

ABBREVIATIONS

AREC	: Agriculture Research and Education Center
CFD	: Computational fluid dynamics
DEC	: Direct evaporative cooling
DPIEC	: Dew point indirect evaporative cooling
IAQ	: Indoor air quality
LCC	: Life cycle cost ($)
NTU	: Number of transfer units
a	: discount rate (%)
A	: DEC/DPIEC channel area (m^2)
C	: Yearly cost ($)
C_{comp}	: Concentration of species in the compartment (ppm)
C_{gen}	: Species generated in the compartment (ppm)
C_N	: Salvage value ($)
C_p	: Specific heat (J/kg·K)
C_{supp}	: Concentration of species in supply air (ppm).
e	: DEC/DPIEC channel gap (m)
h	: heat transfer coefficient ($W/m^2.K$)
h_m	: mass transfer coefficient (m/s)
I	: Horizontal solar radiation (W/m^2)
I_0	: Initial investment ($)
L	: DEC/DPIEC channel length (m)

$\dot{m}_{DEC,tunnel}$: Supply air flow rate into the DEC + tunnel ventilation (kg/s)

$\dot{m}_{DPIEC,loc}$: Supply air flow rate into the DPIEC + local ventilation (kg/s)

$\dot{m}_{DPIEC,tunnel}$: Supply air flow rate into the DPIEC + tunnel ventilation (kg/s)

$\dot{m}_{supp}$: Supply air flow rate into the poultry house compartment (kg/s)

$\dot{m}_{w}$: Supply water flow rate into the DEC or DPIEC apparatus (kg/s)

N : Holding period (years)

$N_{channels}$: Number of channels in DEC and DPIEC units

$Q_{envelope}$: Internal heat gain from compartment envelope (W)

Q_{hens} : Internal heat gain from hens (W)

$\dot{Q}_{w_{DEC,tunnel}}$: Water consumed by the DEC + tunnel ventilation (kg/s)

$\dot{Q}_{w_{DPIEC,loc}}$: Supply air flow rate into the DPIEC + local ventilation (kg/s)

$\dot{Q}_{w_{DPIEC,tunnel}}$: Supply air flow rate into the DPIEC + tunnel ventilation (kg/s)

$RH_{ambient}(\%)$: Ambient relative humidity (%)

$RH_{comp}(\%)$: Compartment relative humidity (%)

T : time (s)

$T_{ambient}$: Outdoor ambient temperature (°C)

T_{comp} : Compartment temperature (°C)

th : DEC/DPIEC sheet thickness (m)

T_{w} : Water film temperature (°C)

T_{wb} : Wet bulb temperature (℃)

U : Overall heat transfer coefficient (W/m.K)

u_{d} : Velocity of air in DEC and DPIEC channels (m/s)

V_{space} : Compartment volume (m^3)

w : DEC/DPIEC channel width (m)

ω_{sat} : Saturation humidity of the water film (g/kg)

x : x-coordinate (m)

y : y-coordinate (m)

Greek symbols

ρ : Density (kg/m^3)

ω : Specific humidity ratio (g/kg)

Subscripts

dc : dry channel

i : year index

out : outlet

pa : product air

s : Species index (CO_2, NH_3, H_2O)

w : water

wa : working air

wc : wet channel

wv : water vapor

ILLUSTRATIONS

TABLES

CHAPTER 1

INTRODUCTION

Over the recent years, the poultry industry has occupied an essential role among agricultural industries in many parts of the world including many countries in the Arab region [1]. Lebanon alone has more than 10 large poultry producers and around 2000 poultry farms that yield around 150 million kilos of broiler meat and eggs that satisfy both local and regional needs [2]. Therefore, maintaining bird health is of critical importance for a sustainable production quality [3]. The welfare of laying hens in poultry houses is highly dependent on the thermal environment and indoor air quality (IAQ) [4, 5]. Typical recommended temperatures and relative humidity (RH) fall in the range of 20 – 24°C and 50 – 70 % respectively [6, 7]. On the other hand, IAQ is mainly dependent on diluting CO_2 from the hens' respiratory activities and NH_3 emitted from poultry litter to limit concentrations to safety standards of 2500 ppm and 25 ppm respectively [6, 7]. Hot and highly humid conditions in poultry houses as well as high concentrations of gaseous contaminants, can be detrimental to both birds' and workers' wellbeing and hence production quality. Consequently, sustainable ventilation designs that are able to meet both cooling and IAQ requirements in poultry houses are needed.

Conventional ventilation designs usually adopted in poultry houses implement passive cooling techniques such as direct evaporative cooling (DEC) in conjunction with different air distribution systems such as mixed ventilation and tunnel ventilation [8-10]. DEC cools the air through evaporation of water and can thus, lower the air temperature down to its wet bulb temperature. This may be insufficient in poultry houses where high heat loads are present (e.g. hot climates) [11]. Hence, large amounts of fresh air may be needed to meet the cooling requirements. Moreover, in the case of humid climates where high wet bulb temperatures are found, temperature requirements might not be attained in the poultry house despite increasing the fresh air supply. This can have negative effects by increasing the water consumption of the DEC system, the electrical energy consumption (fan power, pumps…) and the overall cost of the installed apparatus [12]. In addition, due to the direct contact of the supply air with the evaporating water, humidity levels in the space may increase and become challenging to regulate depending on the outdoor humidity levels. High moisture levels in poultry houses can increase ammonia NH_3 production, wet the poultry manure and harm the health and comfort of laying hens [13, 14].

An advancement on the DEC system would be the Maisotsenko cycle (M-cycle) [15]. The M-cycle is a dew point indirect evaporative cooling (DPIEC) apparatus that can indirectly cool the supply air below its wet bulb temperature, and in some cases down to its dew point temperature without increasing its moisture content. Therefore, it has a larger cooling capacity than the DEC system. In fact, by reaching lower temperatures, the DPIEC apparatus can meet the cooling and IAQ requirements in poultry houses at a lower supply flow rate than the DEC [16]. Thus, it can provide the laying hens with a comfortable thermal environment with acceptable humidity levels. The DPIEC system in cross flow configuration has been previously used in the building sector and has proven successful especially in hot and dry climates [17, 18]. Miyazaki et al. [19] developed a mathematical model of a DPIEC unit driven by a solar chimney for an office space. It was found that the system could reduce the cooling load by more than 10%. Therefore, the DPIEC apparatus is a viable system that can be used in poultry houses located in hot and semiarid climates such as the Beqaa region in Lebanon.

Despite the promising enhancements presented by the DPIEC system, it is still an evaporative-cooling based system. Hence, large amounts of water are still needed to attain the load, which may not be a good option in regions where water sources are scarce [16]. To reduce water consumption, this requires a reduction in the amount of fresh air that is being supplied inside the poultry house. To be able to do so without compromising IAQ, the air distribution system inside the poultry house should be carefully designed. Conventional air distribution systems in poultry houses aim to attain homogenous temperature and air quality. An improvement on conventional systems is a localized air distribution system. The latter directly targets the hens' thermal comfort and fresh air needs by supplying the air directly towards the hen-occupied zone. Localization of supply air in ventilation designs is a technique that has been applied in small-scale occupied spaces in the building sector. It has proven to reduce energy consumption compared to ventilation systems that condition the entire space volume, while meeting occupants' comfort and IAQ needs [20-24]. To the authors' knowledge, no research studies of ventilation in poultry house, have tackled the combination of DPIEC system with a localized air distribution system to meet the cooling and IAQ requirements.

The aim of this work is to compare the water and energy consumption of DEC and DPIEC apparatus under a conventional air distribution system that attains fully mixed conditions in a poultry house located in the semi-arid Beqaa region of East Lebanon. The performance of the DPIEC with the conventional air distribution will be compared to that with the localized air distribution system. The effectiveness of the combined systems is assessed in terms of their ability in meeting cooling and IAQ requirements. To achieve these objectives, a simplified mathematical model of the DPIEC and DEC system combined with a lumped space model is developed to estimate the supply air conditions (temperature, mass flow rate…) for the mixed air distribution system. For the localized air distribution, the DPIEC model is coupled with a 3D CFD model of a representative compartment in the poultry house. The CFD model is adopted to predict velocity fields, temperature distribution, water vapor (H_2O) and contaminants' (NH_3 and CO_2) concentrations in the space and especially in the occupied zone. A case study is then simulated during the summer season, where the performance of the three passive systems was compared for similar thermal and IAQ requirements in the poultry house. An economical analysis was also performed to assess the economic advantages of installing a DPIEC system and localized type air distribution for poultry house ventilation.

CHAPTER 2

SYSTEM DESCRIPTION

In this work, a poultry house located at the Agriculture Research and Education Center (AREC) in the Beqaa Valley, East Lebanon, was selected. The Beqaa valley region is characterized by a semi-arid climate. The poultry house had a typical rectangular shape of dimensions (13.2 m length × 11.8 m width × 3 m height). Its envelope (walls, floor and ceiling) was constructed with hollow block cement with additional polystyrene insulation added to the ceiling. The flooring was lined with a layer of pine nut shavings that served as a bedding material for the laying hens occupying the poultry house. **Table 1** illustrates the wall composition of the poultry house from outside to inside. The poultry house was divided into 4 compartments on each of the left and right sides, separated by a corridor allowing for workers to pass. **Figure 1** illustrates a schematic of the poultry house design with its 8 compartments. Each compartment in the poultry house contained two pens. Adjacent compartments were separated one from other using mesh walls and the two pens in each compartment were also separated by a mesh wall. Each pen hosted 100 laying hens having an average weight of 1.8 kg each and an age of 65 weeks.

The pens were considered to be fully occupied during the day, with each hen generating 7.51 W and 3.3 W in sensible and latent loads respectively [7]. The hens were located at a height of 20 cm. Due to hens' respiratory activities, carbon dioxide CO_2, and water vapor (H_2O) were generated. According to the studies of Shepherd et al. [25], the CO_2 and H_2O generation rates were equal to 75.9 g/day·hen and 2.1 g/hr·hen during summer conditions. On the other hand, poultry manure emits an array of harmful volatile organic compounds, such as methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3) with ammonia constituting 90% of the total mass of emitted gases. According to Calvet et al. [26], the NH_3 generation rate was equal to 0.47 g/day·hen during summer conditions. In order to preserve the laying hens' health and productivity, the temperature in each compartment and especially in the hens' occupied zone must not drop below the lowest allowable temperature of 20 °C nor rise above the highest allowable temperature of 24 °C [6]. A temperature of 24 °C was adopted in this work since summer conditions were considered. To maintain bird welfare, IAQ requirements in the poultry house must be met where the room air, at the hens' level, must be maintained at a relative humidity of 50 - 70 %, and maximum NH_3 and CO_2 concentrations of 25 ppm and 2500 ppm respectively [27].

Table 1. Wall composition (outer to inner), roof and floor composition (outer to inner) for the poultry house

Wall composition			
	Heat transfer coefficient (W/m·K)	**Density (kg/m^3)**	**Specific heat (kJ/kg·K)**
20 mm Plaster	0.18	37.20	1.00
200 mm Hollow Block concrete	0.20	300.00	0.80
15 mm Plaster	0.18	27.90	1.00
Ceiling composition			
100 mm Hollow Block concrete	0.20	300.00	0.80
30 mm polystyrene insulation	0.03	52.3	1.40
Floor composition			
200 mm Hollow Block concrete	0.20	300.00	0.80
50 mm Pine nut shavings	0.11	510.00	2.30

To meet the cooling requirements and provide good IAQ in the poultry house, two passive cooling systems were installed in conjunction with a conventional mixing air distribution system based on the tunnel ventilation adopted by Tong et al. [28]. The latter supplied air from the ceiling level while exhaust fans were located at the far-end west wall such that uniform conditions of temperature and IAQ were achieved [28]. As for the passive cooling systems, the first was the conventional DEC typically used in poultry houses. The second passive system that can reduce energy consumption compared to the DEC system was a cross flow DPIEC apparatus. A cross flow DPIEC system was chosen due to its higher cooling capacity compared to a counter flow design, easier construction and commercial availability [29, 30]. **Figure 1** illustrates the operation of the DEC/DPIEC units combined with the conventional air distribution.

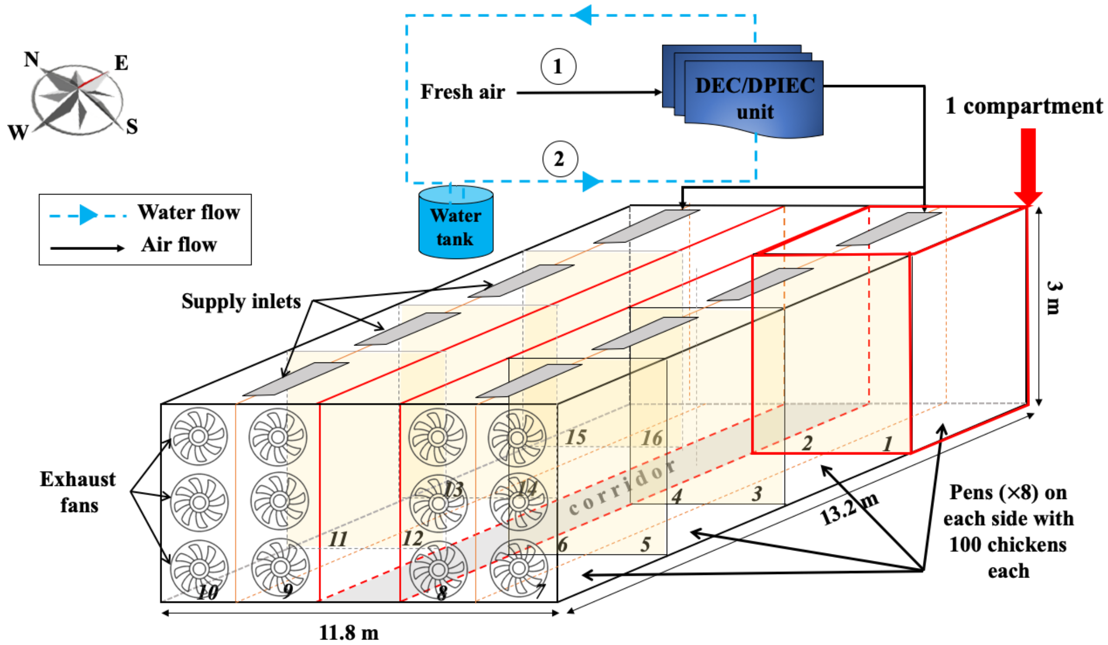

Fig. 1. Illustration of the poultry house design conditioned by the DEC/DPIEC units in conjunction with conventional tunnel air distribution.

The poultry house space was cooled modularly using the passive systems, where each compartment formed by two pens represented a module. The reason for using modular cooling is due to the symmetry present in the poultry house construction. Note that the corner modules were considered as they have two external walls and thus the highest loads among the poultry house compartments. Fresh air was supplied at (1) to either the DEC or the crossflow DPIEC system in order to cool it down to the required temperature before delivering it to each compartment in the poultry house. Note that the DEC and DPIEC units were fed by a water tank at (2). The quantity of fresh air supplied to the space depends on the internal load, outdoor conditions, as well as thermal and IAQ requirements. For the conventional air distribution (**Fig. 1**)**,** the conditioned fresh air exiting the DEC or DPIEC units was supplied to inlet diffusers located at the ceiling level spanning the length of the poultry house (**Fig. 1**).

To improve the performance and downsize the DPIEC intake air flow rate, a localized air distribution system was proposed in this study to replace the conventional mixing air distribution system. **Figure 2(a)** illustrates the DPIEC apparatus combined with the proposed localized air distribution system and **Fig. 2(b)** shows a close up of one compartment conditioned by the proposed system. For the localized air distribution system proposed in this work (**Fig. 2**), the conditioned fresh air from the cross flow DPIEC was delivered to a supply duct spanning the length of the poultry house as seen in **Fig. 2(a)**. In each compartment of the poultry house (**Fig. 2(b)**), a slot diffuser having an inclination angle of 45° was installed. The inclined supply angle allowed for the conditioned fresh air to be supplied directly towards the hens-occupied zone, instead of mixing with the entire compartment air. The air was exhausted from each compartment from exhaust diffusers situated at the north and south walls (**Fig 2(a)**). Note that the exhaust grills were located at a distance of 1 m above floor level and had a large outlet area of 0.66 m^2. This was to avoid resuspending particulate matter from the poultry litter and bedding on the floor, as the latter can be harmful to bird health. A velocity smaller than 1 m/s is preferred at the chicken level to maintain bird comfort without increased ‘windchill’ effect and avoid any disturbance of the poultry house floor bedding and litter [28, 31, 32].

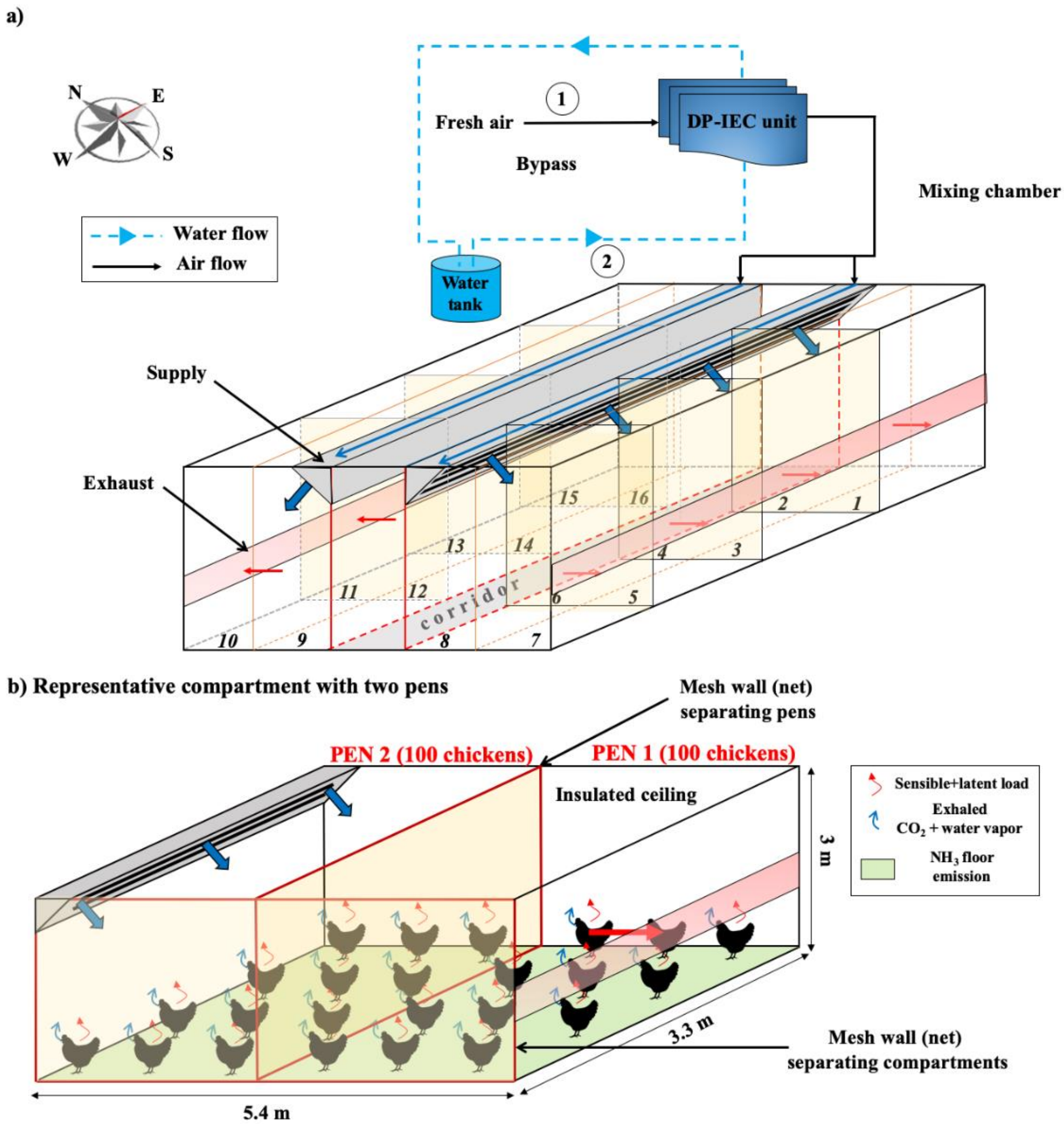

Fig. 2. Illustration of: a) the cross flow DPIEC unit integrated with the proposed localized air distribution system, b) close-up of one compartment (2 pens) in the poultry house.

CHAPTER 3

METHODOLOGY

In this work, three passive cooling systems were considered: DEC + tunnel ventilation, DPIEC + tunnel ventilation and DPIEC + localized ventilation. The objective of this work is to compare the needed fresh air supply and water consumption for these three systems such that a common temperature of 24±0.5°C, a RH(%) range of 50-70% and contaminants concentrations <2500 and <25 ppm for CO_2 and NH_3 respectively are satisfied. For the DEC/DPIEC + tunnel ventilation, these requirements are evaluated in the space since homogeneous conditions are considered while for the DPIEC + localized ventilation, these requirements are evaluated at the chicken height (z = 0.2 m) due to non-homogeneous conditions.

To determine the hourly variation of temperature, internal loads, humidity and contaminants' concentration in each module, an appropriate model is needed for the poultry house compartment. For the compartment equipped with the conventional tunnel ventilation system (**Fig. 1**), a simplified mathematical space model was adopted since homogeneous conditions of temperature and IAQ were considered. The output peak load from the compartment space model was used as input into mathematical models of the DEC/DPIEC systems to size their components (channel width, length, gap size, number of channels). Once the DEC/DPIEC system components are adequately sized, the DEC/DPIEC mathematical models are used to predict the hourly variation of the mass flow rate, temperature and humidity content of the supply air entering the poultry house module as well as the systems' water consumption. The DEC/DPIEC supply flow rate and temperature should be able to meet the thermal and IAQ requirements of the poultry house. Note that for the localized air distribution system, due to the heterogeneity of the flow field variables (temperature, species' concentration), a CFD model was developed for the poultry house compartment. The CFD model boundary conditions were taken as input from the compartment space model (envelope boundary conditions) and the DPIEC model (supply temperature, reduced supply mass flow rate).

The following sub-section presents the compartment space model followed by the mathematical models of the DEC and DPIEC units including their energy and mass balances and the sizing of the systems' components based on peak load removal. The numerical CFD model of the localized air distribution will be presented next.

3.1 Compartment space model

The poultry house compartment conditioned by the tunnel ventilation system was considered to achieve well-mixed and homogeneous conditions of temperature, RH (%) and IAQ. For this reason, a simplified mathematical model that solves for the energy and mass balance (water vapor, CO_2 and H_2O) in the space was developed. The compartment space model was used to determine the hourly variation of the cooling load (sum of internal heat gains from the hens and convective heat exchange between envelope and compartment air), indoor temperature, relative humidity and species' concentration. Equations (1) and (2) represent the energy and mass balance equations for the space:

$$\rho_{air} V_{space} C_{p_{air}} \frac{dT_{comp}}{dt} = \dot{m}_{supp} C_{p_{air}} \left(T_{supp} - T_{comp} \right) + Q_{hens} + Q_{enveloppe}(t) \quad (1)$$

The left side of equation (1) represents the transient heat stored in the poultry house compartment. The first term on the right hand side represents the net convective heat flow, $Q_{hens}(W)$ is the sensible heat generation due to the metabolic activity of hens and $Q_{enveloppe}(t)(W)$ is the convective heat exchange between the space and the poultry house envelope (walls, floor, and ceiling). Note that to solve for the walls' inner surface temperature, the model of Yassine et al. [33] was adopted. T_{comp} is the space temperature which should be optimally equal to 24°C. T_{supp} & $\dot{m}_{supp}(kg/s)$ are the inlet supply temperature and mass flow rates from either the DEC or the DPIEC apparatus respectively. ρ_{air} is the air density, V_{space} is the volume of the poultry house and $C_{p_{air}}$(J/kg.K) is the specific heat of air. The mass balance of moisture, and contaminants in the space are given in equation (2) as follows:

$$\rho_{air} V_{space} \frac{dC_{comp,s}}{dt} = \dot{m}_{supp}\left(C_{supp,s} - C_{comp,s}\right) + C_{gen,s} \quad (2)$$

The terms on the left hand side of equation (2) represent the transient storage term for species (water vapor, CO_2, NH_3) in the poultry house space. The first term on the right hand side represents the net mass transfer. The second term on the right in equation (2) represents the contaminants' generation in the space (CO_2 and NH_3) and moisture generation taken as input from the study of Calvet et al. [25]. $C_{comp,s}(ppm)$ and $C_{supp,s}(ppm)$ are the concentration of species *s* (*i* denotes either CO_2 and NH_3 or H_2O) in the poultry house space and supply air respectively. Note that for the water vapor, $C_{supp,i}(ppm)$ is taken as input from either ambient conditions for the DPIEC + tunnel ventilation and from the DEC humidified air for the DEC + tunnel ventilation system.

3.2 DEC/DPIEC models

The DEC/DPIEC units that need to be installed for one poultry house compartment should be sized such that they are able to remove the peak load of the summer season.

The components of the DEC/DPIEC systems that need to be sized are the channel width *w* and length *L*, channel gap size *e*, inlet velocity u_d in each channel and hence the number of channels $N_{channels}$. **Figure 3** illustrates detailed schematics of the DEC/DPIEC units with their respective dimensions. Once the DEC/DPIEC units are adequately sized, the DEC/DPIEC mathematical models take as input: the hourly variation of ambient fresh air conditions (ambient temperature $T_{ambient}$, and relative humidity $RH_{ambient}$ *(%)*). Subsequently, by solving for the energy and mass balance for the intake air inside the channels the models output: the hourly air supply flow rate such that temperature, and IAQ requirements are met as well as the DEC/DPIEC water consumption.

The DEC system is composed of consecutive wet channels equipped with cooling pads wetted with water originating from a feeder tank. The product air constituted mainly of the ambient fresh air passes through the wet channels. Due to the direct contact with the cooling pads, the product air is cooled due to water evaporation and its moisture content increases (**Fig. 3(a)**). The DEC mathematical model is solved based on heat and mass transfer between the product air in the wet channels and the water film. It solves for the product air and water film temperatures variation ($T_{pa}(y)$(°C) and $T_w(y)$(°C) respectively) as well as the variation of the humidity content of the product air $\omega_{pa}(y)$ (kg/kg$_{air}$) the y-direction (**Fig. 3(a)**). Equation (3) presents the energy balance between the product air and the water while equation (4) presents the mass balance between the product air and the water.

$$\frac{\partial T_{pa}}{\partial y} = \underbrace{\frac{h_{pa}A}{C_{p_{pa}}\,\dot{m}_{pa}L_{wc}}\left(T_w - T_{pa}\right)}_{sensible} + \underbrace{\frac{C_{p_{wv}}\partial\omega_{pa}}{C_{p_{pa}}\,\partial y}\left(T_w - T_{pa}\right)}_{latent} \quad (3)$$

$$\frac{\partial \omega_{pa}}{\partial y} = \frac{h_m A}{L_{wc}\dot{m}_{pa}}\left(\omega_{sat} - \omega_{pa}\right) \tag{4}$$

where ω_{sat} is the saturation humidity of the water film. h_{pa} (W/m^2.K) is the heat transfer coefficient of the product air while h_m is the mass transfer coefficient according to Lewis relation. $\dot{m}_{pa}$(kg/s) is the mass flow rate of the product air, L_{wc}(m) is the length of the wet channel. Cp_{wv} (J/kg.K) and Cp_{pa} (J/kg.K) are the specific heat of water vapor and moist product air respectively. A (m^2) is the area through which the heat and mass exchange occurs. Moreover, the energy balance of the water film can be seen in equation (5):

$$\frac{\partial T_w}{\partial y} = \frac{h_{pa} A}{\dot{m}_w C_{p_w} L_{wc}}\left[\left(T_{pa} - T_w\right) - \left(\frac{C_{p_{wv}} - C_{p_w}}{C_{p_{pa}}} T_w + \frac{h_{fg}}{C_{p_{pa}}}\right)\left(\omega_{sat} - \omega_{pa}\right)\right] \tag{5}$$

Where $\dot{m}_w$ (kg/s) is the water mass flow rate into the system, C_{p_w} (J/kg·K) is the specific heat capacity of water and h_{fg} (J/kg) is the latent heat of vaporization of water. The water consumption of the system is shown in equation (6):

$$WC = \frac{\dot{m}_{pa}}{\rho_{air}}\left(\omega_{amb} - \omega_{out,pa}\right) \times 3600 \tag{6}$$

where WC (l/h) is the water consumption of the DEC system, ω_{amb} (kg/kg$_{air}$) and $\omega_{out,pa}$(kg/kg$_{air}$) are the specific humidity ratios of the ambient air entering the DEC and the product air discharged from the DEC.

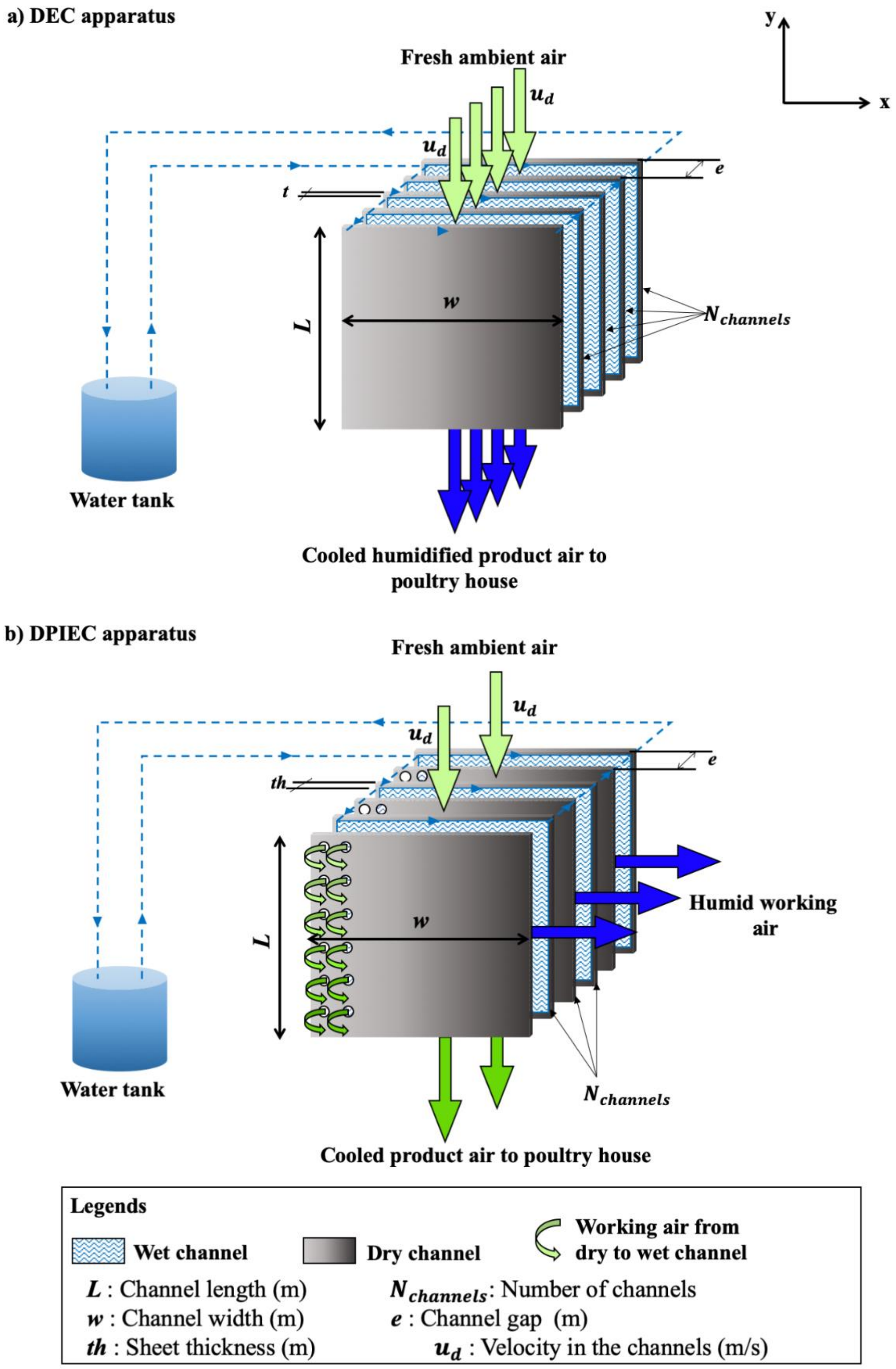

Fig. 3. Schematic of: a) the DEC system and b) the perforated cross flow DPIEC system.

As for the cross flow DPIEC heat and mass exchanger **(Fig. 3(b**)), a perforated design, similar to that modeled by Anisimov et al. [29] was adopted. It constitutes of dry and wet channels, where the fresh air intake is divided into two streams of product and working air. The product air passes in the dry channels where it is sensibly cooled while the working air is sensibly pre-cooled in the dry channel as well while being simultaneously diverted into the wet channel through regularly distributed perforations. While in the wet channel, the working air absorbs the heat released from the product air in the dry channel and the evaporated water before being discharged as hot humid air. The DPIEC mathematical model based on the ε-NTU method of Asiminov et al. [29] solves the heat and mass balance equations in the dry and wet channels of the cross flow DPIEC in a control volume defined by half length of the dry and wet channels and the water non-permeable wall separating them. Thus, it computes the product air and water film temperatures variation in the y-direction ($T_{pa}(y)$(°C) and $T_w(y)$(°C) respectively) (**Fig. 3(b)**). It also computes the working air temperature and humidity content variation in the x-direction ($T_{wa}(x)$(°C) and ω_{wa} (kg/kg$_{air}$). The 2D model assumes steady periodic conditions with adiabatic process (no heat exchange with surrounding) and constant thermal properties [29]. Heat exchange occurs in the dry channel while both heat and mass exchange occur in the wet channel. The energy balance in the dry channel (along y-direction) presented in equation (7) accounts for the sensible heat exchange between the water and product air stream due to convection and conduction through the channel walls as follows:

$$\frac{\partial T_{pa}}{\partial y} = \frac{U\,A}{\dot{m}_{pa}\,Cp_{pa}\,L_{dc}}\left(T_w - T_{pa}\right) \tag{7}$$

where $\dot{m}_{pa}$(kg/s) and Cp_{pa}(J/kg.K) are the flow rate and specific heat of the product air, L_{dc}(m) is the length of the dry channel, U (W/m^2.K) is the overall heat transfer coefficient and A (m^2) is the area through which the heat exchange occurs. In the wet channel, mass and energy transfer take place between the working air and the water film. The energy and mass balance equations in the DPIEC wet channel (along x-direction) are the same as equations (1) and (2) for the product air in the DEC apparatus. However, the product air properties are replaced with the DPIEC working air properties $(T_{wa}, \omega_{wa}, h_{wa}, C_{p_{wa}})$. On the other hand, the energy balance for the water film is shown in equation (8):

$$\frac{\partial T_w}{\partial x} = \frac{UA}{\dot{m}_w C_{p_w} L_{dc}} + \frac{h_{wa} A}{\dot{m}_w C_{p_w} L_{wc}} \left[(T_{wa} - T_w) - \left(\frac{C_{p_{wv}} - C_{p_w}}{C_{p_{wa}}} T_w + \frac{h_{fg}}{C_{p_{wa}}} \right) (\omega_{sat} - \omega_{wa}) \right] \quad (8)$$

As for the DPIEC water consumption, it was calculated based on equation (6) for the product air exiting the dry channels of the system.

Note that the energy and mass balances of the compartment space model, DEC and DPIEC models were discretized using a simplified transient numerical model code written in MATLAB. The numerical model consisted of an implicit first-order time integration scheme. After performing a time-step independence test, a time step of 3600 s was adopted. A steady periodic solution was reached following the repetition of simulations over a number of cycle days. The convergence criterion was set when the residuals of the temperature between two consecutive iterations is less than 10^{-5} °C [34, 35].

3.3 CFD modeling of localized air distribution system

The proposed localized air distribution system establishes non-uniform conditions of temperature and contaminants' concentration in the space. Consequently, to solve for the velocity, pressure and thermal fields, as well as the concentration of the different species, a 3-D CFD model of a poultry house compartment was developed. Only one compartment was considered due to the symmetry of the poultry house geometry (**Fig. 2**). Note that a corner compartment having two external walls was selected since it has the highest cooling load requirements. The commercial software ANSYS Fluent version 17.2 [36] was used to solve for the different variables in the space. The computational domain of the space with its different components can be seen in **Fig. 4**. The hens were represented by computational 3D models acquired from CG trader library [37, 38].

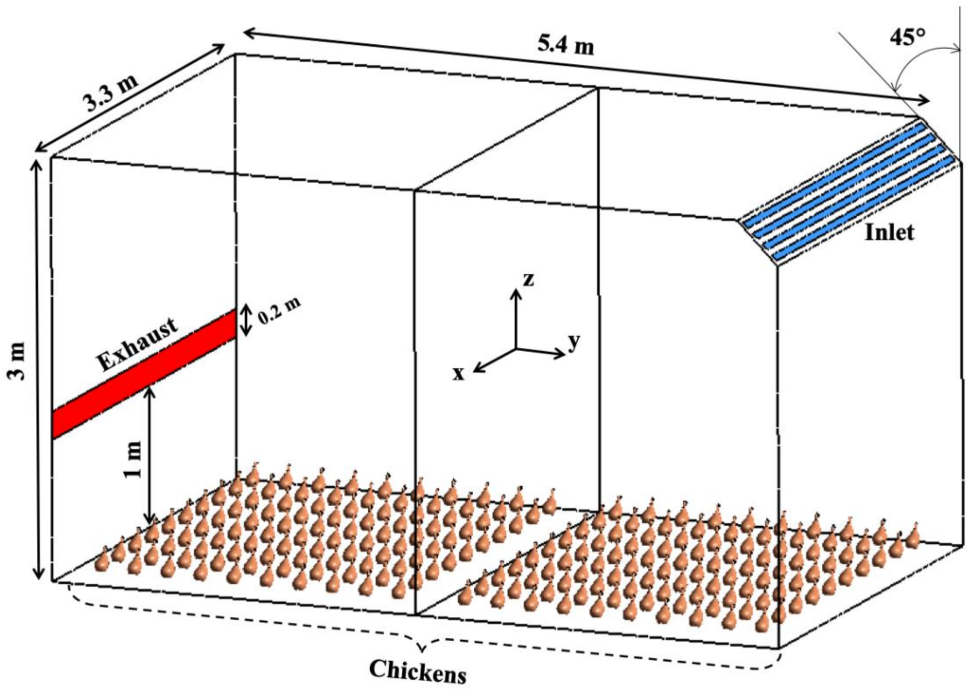

Fig. 4. Illustration of the modular computational domain as seen in ANSYS Fluent

3.3.1 Airflow modeling

In order to solve the different flow field variables accurately, an appropriate mesh was implemented for the considered computational domain as seen in **Fig. 5**. The space was meshed with an unstructured grid with tetrahedral shaped elements. Face sizing of 1.5 cm and 4 cm were set for the inlet/outlet of the ventilation system and walls respectively. Face sizing of 1 cm and 3 mm was adopted at the hens' boundaries and their nostrils respectively. Note that the grid had a maximum skewness of 0.83. Moreover, the final grid choice ensured a mesh independent solution with a maximum relative error of less than 5%. The relative error was defined based on the difference of average velocities between two consecutive mesh configurations, in the cross-sectional plane of the space. The different mesh cases can be seen in **Table 2**. The mesh was characterized by 5,352,533 elements.

Table 2. Grid independence test using five different mesh cases.

	Face sizing hens/walls (cm)	**Number of elements**	**Relative error between two consecutive meshes (%)**
Mesh 1	2/8	5,159,593	-
Mesh 2	2/6	5,278,144	28.4
Mesh 3	1.5/6	5,281,408	17.4
Mesh 4	1.5/4	5,292,233	10.1
Mesh 5	1/4	5,352,533	4.8

Accurate prediction of the airflow pattern is essential for correct estimations of the IAQ and temperature in the hens' occupied zone. The RANS model and more specifically the RNG k-ε model was chosen as a compromise between computational cost and accuracy. Note that the RNG k-ε model adopts wall functions to consider wall effects on turbulence. In this work, the enhanced wall treatment was used. The Boussinesq approximation was used to account for buoyancy driven flows, as no density gradients existed in the space except those affected by gravitational acceleration [39]. Note that the momentum, energy, k, ε equations were discretized using the second order upwind scheme. As for pressure, the “PRESTO!” scheme was used since it accounts for pressure gradients at the boundaries [34]. As for the pressure-velocity coupling, the “SIMPLE” algorithm was chosen [40]. For a converged solution, several criteria were applied. The scaled residuals were lower than 10^{-8} for the energy equation and lower than 10^{-6} for the rest of the variables [21-24, 41]. Moreover, the net heat flux was 1% less than the total heat gained and mass balance was ensured in the space.

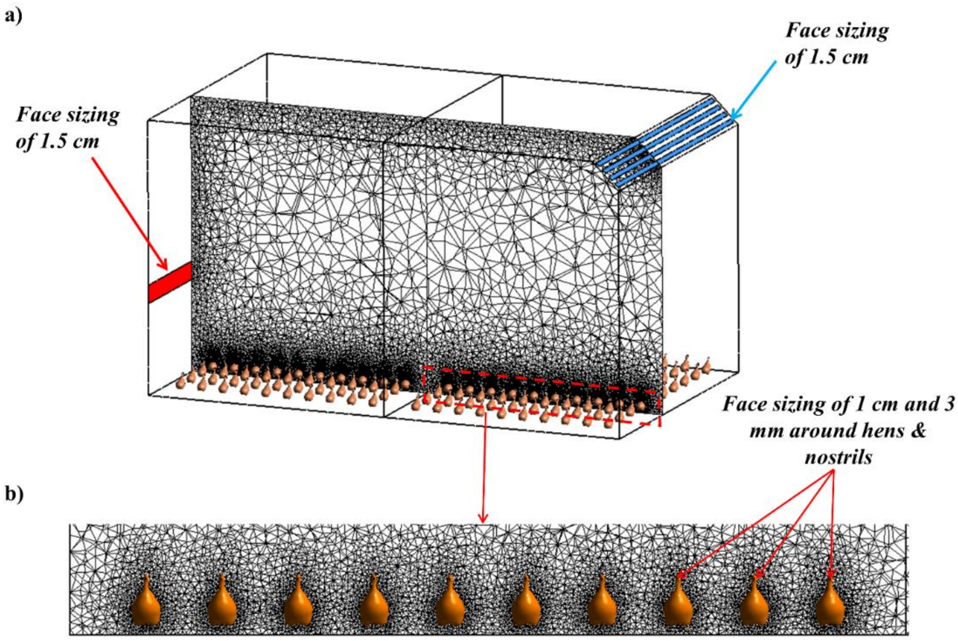

Fig. 5. Illustration of: a) the adopted mesh of the poultry house compartment at the x = 1.2 m plane, and b) close-up of the grid refinement near the hens.

3.3.2 Boundary conditions

For an accurate physical solution of the considered space, correct assignment of the boundary conditions in the poultry house compartment is crucial. The four supply slots were considered as velocity inlets with constant supply velocity, temperature, turbulence intensity and hydraulic diameter. The supply CO_2 concentration was equal to that of the ambient fresh air (400 ppm), while that of NH_3 was equal to 0 ppm. The H_2O concentration was equal to that of the ambient fresh air, which is equal to that of the DPIEC cooled air output since the latter does not affect the moisture content of the supplied air. The exhaust was selected as a pressure outlet with zero-gauge pressure, specified turbulence intensity and hydraulic diameter. The laying hens were assigned as walls with constant heat flux. The hens' nostrils located at a height of 20 cm from the floor were assigned as velocity inlets generating CO_2 and H_2O at constant rates and a constant supply velocity. Note that the breathing of the hens was simplified to a steady state exhalation due to the small nostril area. The walls, ceiling and floor were considered as walls with constant room-side surface temperature taken as input from the space model during a typical day of each summer month. Note that the floor was also considered to be generating a diffusive flux of NH_3. The internal net walls were considered as symmetry walls. **Table 3** represents a detailed summary of the boundary conditions for the poultry house compartment.

Table 3. The boundary conditions used for the different components of the poultry house

Boundary conditions used for CFD model	
Boundary	**Condition**
Supply slot (×4)	Velocity inlet (constant value) Constant inlet temperature: Input from DPIEC model depending on supply flow rate. Turbulence intensity: 5 % Hydraulic diameter: 0.1 m $C_{CO_2} = 400\ ppm$ (ambient) $C_{NH_3} = 0\ ppm$ (ambient) C_{H_2O} = specific humidity ratio from DPIEC model output (kg/kg)

Boundary conditions used for CFD model	
Boundary	**Condition**
Exhaust	Pressure outlet, zero-gauge pressure Turbulence intensity: 5 % Hydraulic diameter: 0.37 m
Hens	Wall with constant heat flux (total of 11 W/hen)
Hens’ nostrils	Velocity inlet (constant value): 0.6 m/s (pulmonary ventilation rate) [42] Constant inlet temperature: 34°C Turbulence intensity: 5 % Hydraulic diameter: 0.003 m $C_{CO_2} = 81600\ ppm$; [25] $C_{NH_3} = 0\ ppm$ C_{H_2O} = 86000 ppm [25]
Ceiling, walls	Fixed walls with constant inner surface temperatures taken as input from the compartment space model
Floor	Fixed walls with constant temperatures input from the space model with diffusive flux of NH_3 [26]

CHAPTER 4

SOLUTION METHODOLOGY

In order to meet a temperature of 24±0.5°C, RH(%) between 50-70% and IAQ (CO_2 and NH_3) requirements in the space (<2500 ppm and <25 ppm respectively), fresh outdoor air was supplied. The latter was passed through either a DEC or DPIEC system to meet the cooling load before being supplied through tunnel ventilation or the proposed localized ventilation system. The presented mathematical and CFD models that were presented were coupled one with the other according to the flowchart presented in **Fig. 6**.

The compartment space model takes as input the geometrical and thermal properties of the building envelope, hourly outdoor conditions (temperature, humidity ratio, contaminants' concentration), indoor required set point, as well as the hens' and manure contaminants generation rates. It outputs the hourly cooling load for the five months of the cooling season as well as the minimum required fresh air supply flow rate to remove the peak load, and meet thermal and IAQ requirements. The latter were taken as input into the DEC/DPIEC models, along with the outdoor conditions (ambient temperature, humidity ratio) and water supply flow rate to size the system components (channel width, length, gap size, channel velocity and number of channels) such that it is able to remove the maximum peak load found during the summer season. Once the DEC/DPIEC units are sized for each compartment, the DEC/DPIEC model solves for the hourly variation of the air supply flow rate ($\dot{m}_{DEC,tunnel}(t)$ & $\dot{m}_{DPIEC,tunnel}(t)$) and water consumption ($\dot{Q}_{w_{DEC,tunnel}}(t)$ & $\dot{Q}_{w_{DPIEC,tunnel}}(t)$) of the systems such that thermal and IAQ requirements are met at all times during the day. To be able to compare the performance of these systems, they should achieve the same indoor temperature of 24±0.5°C, indoor RH(%) range of 50-70% and CO_2, NH_3 concentrations of <2500 ppm and <25 ppm respectively. Note that for poultry houses conditioned by tunnel ventilation, an upper limit on the desired supply flow rate should be set such that no 'windchill' effect occurs to the birds due to increased air velocities beyond 1 m/s. According to Tong et al. [28], poultry houses with tunnel ventilation during summer can reach a maximum air change rate of 85 to provide the chickens with a comfortable thermal environment without exceeding velocity guidelines at the chicken level. This corresponds to a supply flow rate of 1.26 kg/s in the case of the poultry house considered in this work. To check this value for the current design, additional CFD simulations of the tunnel ventilated space were conducted for one module. Results showed that a maximum flow rate of 1.1 kg/s can be allowed for the velocity at the chicken level to stay below 1 m/s. Therefore, the lower bound of 1.1 kg/s will be set as the upper flow rate limit that can be supplied from the tunnel ventilated system.

For the DPIEC + localized ventilation, ideally, the CFD model should be simulated for each hour of a representative day for each summer month to determine the DPIEC supply conditions that achieve the same thermal and IAQ requirements as the DPIEC + tunnel ventilation. Subsequently, the supply mass flow rate and water consumption can be adequately compared between the two passive systems. However, this increases computational time and cost and a simplification of the problem was hence required to reduce the number of simulations. This can be done by averaging, for each month and for consecutive hours, similar ambient outdoor conditions that require similar supply conditions from the DPIEC and ensure similar compartment and wall surface temperatures as well as IAQ. The average outdoor conditions can then be taken as input into the sized DPIEC model along with the reduced air supply flow rate $\dot{m}_{DPIEC,loc}$. The model determines the DPIEC supply temperature into the CFD model, and the water consumption $\dot{Q}_{w_{DPIEC,loc}}$ of the localized system. The DPIEC + localized supply conditions (temperature and air flow rate) should be able to achieve similar thermal and IAQ requirements as the DPIEC + tunnel ventilation. Subsequently, $\dot{m}_{DPIEC,loc}$ and $\dot{Q}_{w_{DPIEC,loc}}$ can be compared with the averaged $\dot{m}_{DPIEC,tunnel}$ and $\dot{Q}_{w_{DPIEC,tunnel}}$ respectively.

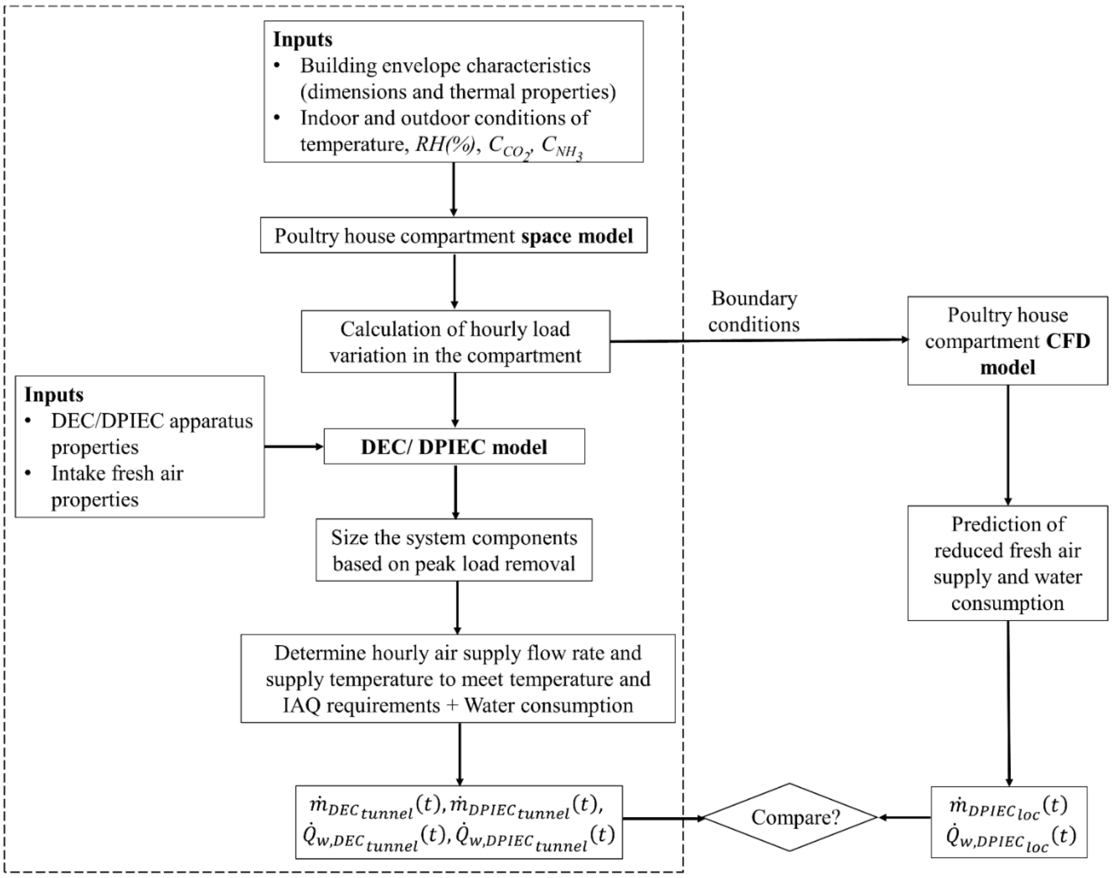

Fig. 6. Illustration of the adopted numerical methodology flowchart.

CHAPTER 5

CASE STUDY

The performance of the three proposed combinations of systems was studied during the summer season where cooling is required; May through September. **Figure 7** illustrates the ambient temperature, relative humidity $RH_{ambient}$ (%) as well as wet bulb and dry bulb temperatures for a representative day of each considered summer month in Beqaa. The horizontal solar radiation *I* (W/m^2) was also presented in **Table 4** for each of the summer months [34] The weather data was obtained from actual measurements at AREC Beqaa taken over a period of five consecutive years [43].

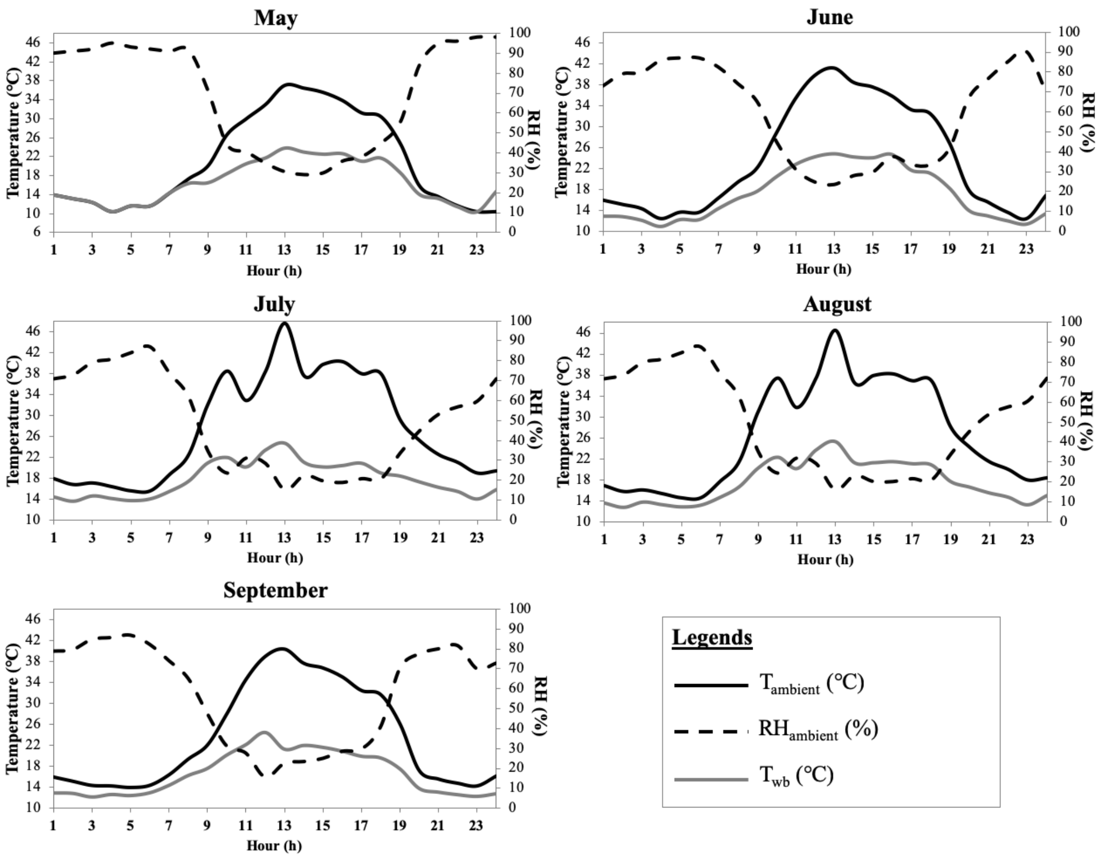

Fig. 7. Hourly variation of the ambient temperature $T_{ambient}$ (°C), $RH_{ambient}$ *(%)* and T_{wb} (°C) for a representative day of each summer month.

Table 4. Hourly variation of the solar radiation on a horizontal surface I (W/m^2) for the representative day of each summer month [34].

Hour	May	June	July	August	September
1:00 AM	0	0	0	0	0
2:00 AM	0	0	0	0	0
3:00 AM	0	0	0	0	0
4:00 AM	0	0	0	0	0
5:00 AM	0	0	0	0	0
6:00 AM	24.4	24.4	24.4	24.4	24.4
7:00 AM	75.8	75.8	66.6	48.2	75.8
8:00 AM	97.2	97.2	93.9	81.8	97.2
9:00 AM	654.7	107.8	106.7	96.0	107.8
10:00 AM	810.0	113.6	113.5	103.1	113.6
11:00 AM	920.3	116.7	117.2	106.9	116.7
12:00 PM	978.4	118.2	119.0	108.7	118.2
1:00 PM	980.3	118.2	119.3	109.0	118.2
2:00 PM	925.9	116.9	118.2	107.8	116.9
3:00 PM	818.8	113.9	115.4	105.0	113.9
4:00 PM	108.3	108.3	110.2	99.4	108.3
5:00 PM	98.2	98.2	100.7	88.9	98.2
6:00 PM	77.8	77.8	81.7	66.0	77.8
7:00 PM	29.3	29.3	36.7	7.8	29.3
8:00 PM	0	0	0	0	0
9:00 PM	0	0	0	0	0
10:00 PM	0	0	0	0	0
11:00 PM	0	0	0	0	0
12:00 AM	0	0	0	0	0

CHAPTER 6

RESULTS AND DISCUSSION

In the following section, the performance of the three proposed systems will be evaluated and compared based on their ability in maintaining a comfortable thermal environment for the laying hens as well as good IAQ. The performance of the DEC/DPIEC + tunnel ventilation was assessed first, followed by that of the DPIEC + localized ventilation.

6.1 DEC/DPIEC units sizing

After obtaining the cooling loads for each month from the compartment space model, it was found that the peak loads were reached during the month of **July**. The cooling load in the poultry house had a daily average of 119 W/m^2 during July, which is a typical cooling load found in poultry houses in hot Mediterranean climates [1, 44]. Following the flow chart presented in **Fig. 6**, the DEC/DPIEC units were sized based on the minimum required supply fresh air (1.1 kg/s and 0.4 kg/s for DEC and DPIEC respectively) needed to remove the compartment peak load (3400 W) found during July while simultaneously meeting RH(%) and IAQ requirements. **Table 5** represents the geometrical characteristics of the DEC and DPIEC units.

Table 5. Geometric and operational parameters of the DPIEC unit.

Parameter	DEC	DPIEC
Channel length (m)	1.2	1.2
Channel width (m)	1.2	1.2
Channel gap thickness (m)	3×10^{-3}	3×10^{-3}
Sheet thickness (m)	0.5×10^{-3}	0.5×10^{-3}

Number of channels	126	95
Ratio of working to product air	-	0.5

6.2 Performance of the DEC/DPIEC + tunnel ventilation

After sizing the systems, simulations were performed for the entire considered cooling season (May through September) to determine the variation in the needed supply fresh air that aims to meet thermal and IAQ requirements in the poultry house compartment for both DEC/DPIEC + tunnel ventilation systems. To be able to compare the DEC and DPIEC systems, they should aim to achieve the same set point of 24±0.5°C inside the poultry house compartment, same RH (%) range of 50-70% and same CO_2, NH_3 concentrations of <2500 ppm and <25 ppm respectively. **Figure 8** illustrates the hourly variation of the air supply flowrate and water consumption for the DEC and DPIEC systems for a representative day of each summer month. The indoor compartment conditions (temperature T_{comp}(°C), RH_{comp} (%), CO_2 and NH_3 concentration (ppm)) hourly variations were depicted in **Fig. 9** and **10**.

According to **Fig. 8**, for all summer months except for May, the needed supply fresh air from the DEC (and hence water consumed) was minimal from 8:00 PM till 8:00 AM (nighttime and early morning) and this is due to the low outdoor temperatures (**Fig. 7**). Therefore, the needed cooling from the DEC was minimal. For example, for the month of July, the average air supply and water consumption were 0.26±0.11 kg/s and 2.12±1.3 l/h. As for the month of May, the outdoor air temperatures from 8:00 PM till 8:00 AM were low enough to meet the cooling load. Thus, the DEC unit was bypassed as natural ventilation was sufficient. According to **Fig. 9** and **10**, during this period, the temperature T_{comp}(°C), relative humidity RH_{comp}(%), and IAQ requirements (C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm)) were compliant with poultry house requirements. For example, for the month of July, the average T_{comp}(°C), RH_{comp}(%), C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were equal to 24.12±0.3°C, 63±3%, 992±100 ppm and 12.4±4 ppm respectively. Note that from 8:00 PM till 8:00 AM (nighttime and early morning), the highest needed flow rates of air and water were found during the month of July.

As for the time interval between 9:00 AM and 7:00 PM (noon and afternoon), and for all the summer months, the needed supply fresh air (and hence water consumed) from the DEC increased due to the increase in outdoor temperatures (**Fig. 7**) and needed cooling power. For example, during the month of July, the average air supply and water consumption were 1±0.2 kg/s and 20.75±4.7 l/h respectively. During this period (especially from 10:00 AM till 5:00 PM) and for all summer months, T_{comp}(°C) and RH_{comp}(%) were not fully compliant with poultry house requirements reaching maximum values of 28°C and 83% during the month of July. This is due to the high wet bulb temperatures (**Fig. 7**) and hence limited cooling capacity of the DEC system, direct humidification of the supply air as well as the upper limit on the DEC supply air flow rate. Similar results were obtained by Dagtekin et al. [45] when studying the performance of a DEC in a poultry house under Mediterranean climates. They reported that the DEC system was most effective during mornings and evenings while during the afternoon, indoor temperatures and *RH(%)* also reached a maximum of 28°C and 88%. On the other hand, during this period, for the DEC, C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were compliant with IAQ requirements for all summer months. For example, for the month of July, the average C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were equal to 541±50 ppm and 2.9±1 ppm respectively. These concentrations are lower than the ones obtained during nighttime and early morning due to the higher supply of fresh air and hence more effective contaminants' dilution during the noon and afternoon (**Fig. 9**).

As for the DPIEC system, it behaved similarly to the DEC with small supply fresh air and water consumption needed during nighttime and early morning (8:00 PM – 8:00 AM). For example, for the month of July, the average fresh air supply and water consumption were 0.21±0.05 kg/s and 2±1 l/h respectively. These flow rates were smaller than the ones needed in the DEC due to the higher cooling capacity of the DPIEC compared to the DEC. Note that the indoor conditions were compliant with the poultry house requirements and were similar to those obtained in the DEC. For example, for the month of July, the average T_{comp}(°C), RH_{comp}(%), C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were equal to 24±0.3°C, 53±5%, 1080 ±100 ppm and 14±2 ppm respectively. RH_{comp}(%) was higher in the case of DEC due to humidification of supply air. On the other hand, the CO_2 and NH_3 concentrations were slightly higher for DPIEC and this is due to its slightly smaller supply fresh air compared to DEC.

As for the DPIEC system performance during daytime (9:00 AM – 7:00 PM), similar to DEC, fresh air supply and water consumption increased to meet the higher cooling load observed during this time. For example, for the month of July, the average fresh air supply and water consumption were 0.4±0.07 kg/s and 9.1±2.6 l/h respectively. However, unlike the DEC, according to **Fig. 9**, during this time of the day, T_{comp}(°C), RH_{comp}(%) were compliant with poultry house requirements. For example, for the month of July, the average T_{comp}(°C), RH_{comp}(%) were equal to 24.3±0.3°C and 50±6% respectively. IAQ requirements (C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm)) were also met using DPIEC during this time. C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were equal to 740±60 ppm and 7.2±1 ppm respectively, slightly higher than those obtained with DEC due to smaller required fresh air supply. These values are lower than the ones obtained during nighttime, due to the higher supply fresh air as well. Notably, during this time of the day, the needed flow rates of air and water were slightly higher (7.5% and 6% for air and water respectively) for the month of June rather than the peak month of July. This is explained by the higher dew point temperatures found in June during this period (**Fig. 7**) requiring a slight increase in needed supply to remove the load.

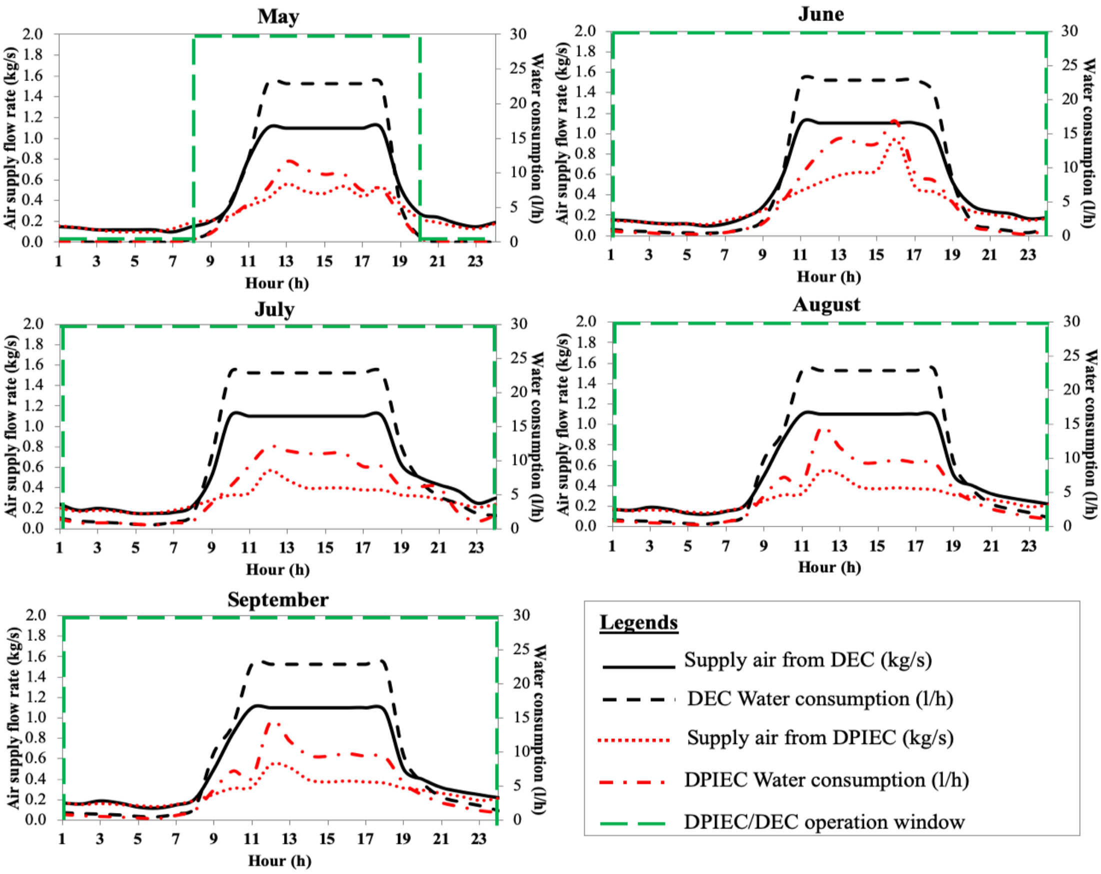

Fig. 8. Hourly variation of the air supply flow rate and water consumption for the DEC and DPIEC systems for a representative day of each month.

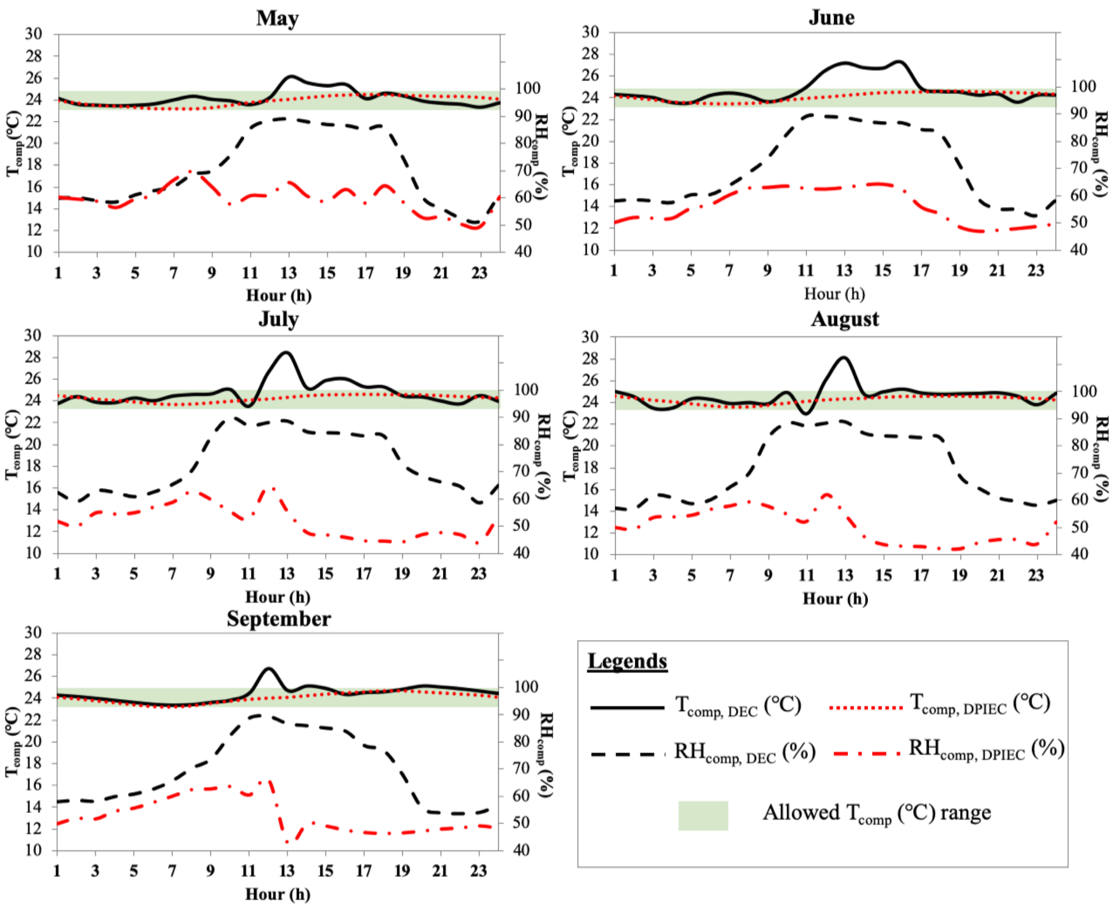

Fig. 9. Hourly variation of the compartment temperature T_{comp} (°C), relative humidity RH_{comp} (%) using DEC and DPIEC for a representative day of each month

Finally, comparing the performance of the DEC and DPIEC systems under tunnel ventilation (**Fig. 8**), it is clear that less fresh air was needed in the case of DPIEC system to condition the poultry house compartment. This is since the DPIEC apparatus can reach lower supply temperatures than the DEC. For example, during the month of July, the DPIEC consumed 52% less fresh air than the DEC to remove the same load. Given this large difference in needed supply fresh air, the water consumption for the DPIEC system was larger than that of the DEC despite needing more energy from water evaporation to reach temperatures closer to the dew point. For example, during the month of July, the DEC consumed 51.3% more water than the DPIEC. Therefore, the DPIEC system is able to satisfy the thermal and IAQ requirements of the poultry house at all times using less power consumption than the DEC. Therefore, its use is beneficial for applications such as poultry house ventilation.

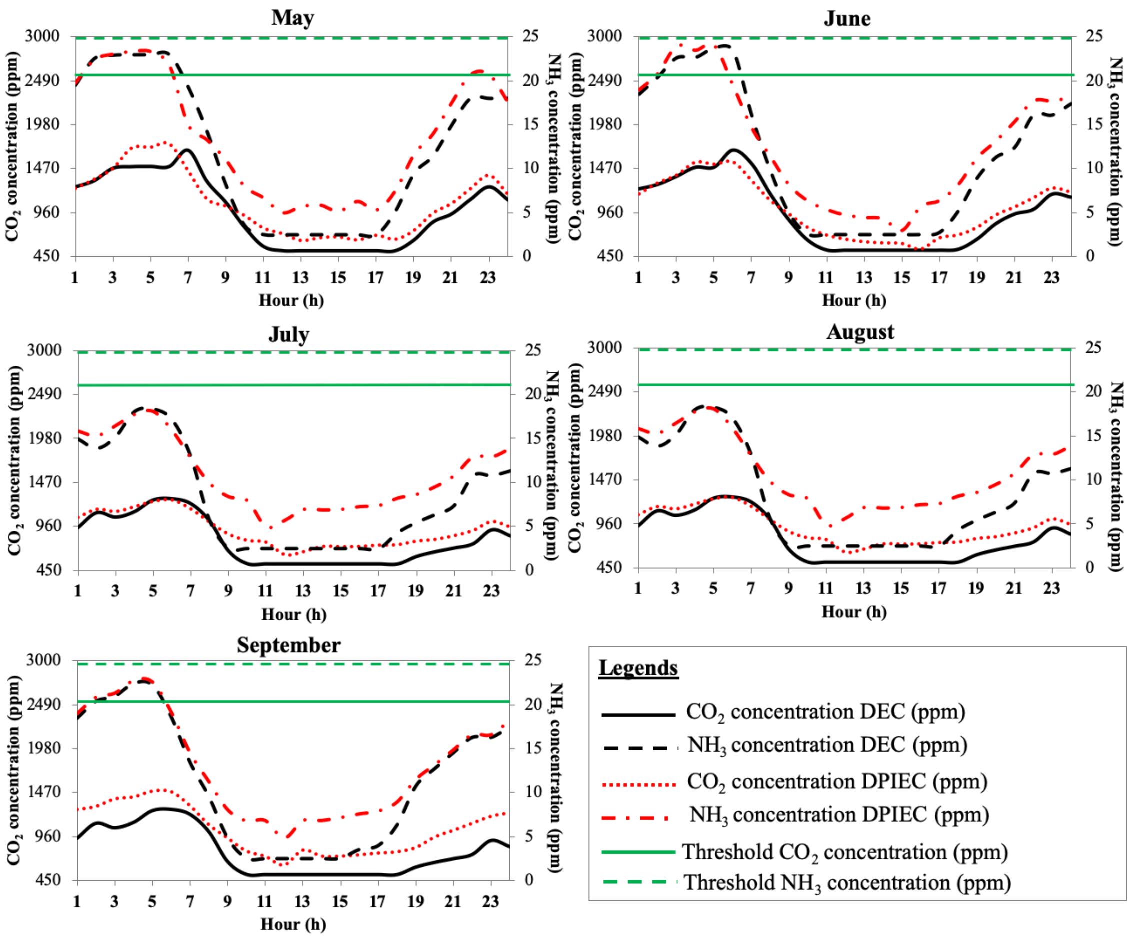

Fig. 10. Hourly variation of the compartment CO_2 and NH_3 concentration (ppm) using DEC and DPIEC for a representative day of each month.

6.3 Performance of the DPIEC + localized ventilation

As previously discussed in the previous section, the DPIEC + localized ventilation was simulated for each summer month for average outdoor conditions for consecutive hours during the day. The DPIEC model was simulated for a reduced fresh air intake compared to the DPIEC + tunnel ventilation. The reduced flow rate of air and its corresponding supply temperature; taken as input into the CFD model should be able to achieve the same indoor conditions as the DPIEC + tunnel ventilation. **Table 6** shows a comparison of the air and water needs for the DPIEC + tunnel ventilation and the DPIEC + localized ventilation systems for a representative day of each month. It also illustrates how the average outdoor conditions were averaged for each month for the CFD simulations. The average outdoor conditions were averaged such that they ensure similar compartment and wall surface temperatures as well as IAQ and thus, require similar supply conditions from the DPIEC.

According to **Table 6**, during nighttime and early morning (8:00 PM – 8:00 AM), similarly to DPIEC + tunnel ventilation, the DPIEC + localized ventilation fresh air and water consumption needs were minimal. For example, for the month of July, the average air supply and water consumption were 0.17±0.04 kg/s and 1.6±0.5 l/h. Therefore, during nighttime and early morning, the DPIEC + localized was able to reduce fresh air intake and water consumption compared to the DPIEC + tunnel ventilation by 19% and 23.8% respectively for July. This trend was consistent throughout May till September (**Table 6**). This reduction is justified by the localization of the supply fresh air directly towards the hen occupied zone instead of fully mixing with the compartment space as is the case with conventional air distribution. During this period, the temperature T_{comp}(°C), relative humidity RH_{comp}(%), and IAQ requirements (C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm)) were compliant with poultry house requirements. For example, for the month of July, the average T_{comp}(°C), RH_{comp}(%), C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were equal to 24±0.3°C, 66±3%, 1000±60 ppm and 10±2 ppm respectively.

During noon and afternoon (9:00 AM – 7:00 PM), similarly to DPIEC + tunnel ventilation, the DPIEC + localized ventilation fresh air and water consumption needs increased. For example, for the month of July, the average air supply and water consumption were 0.31±0.07 kg/s and 7.3±2.2 l/h. Therefore, during daytime, the DPIEC + localized was also able to reduce fresh air intake and water consumption compared to the DPIEC + tunnel ventilation by 20.5% and 19.7% respectively for July. This trend was also consistent throughout May till September (**Table 6**). During this period, the temperature T_{comp}(°C), relative humidity RH_{comp}(%), and IAQ requirements (C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm)) were compliant with poultry house requirements. For example, for the month of July, the average T_{comp}(°C), RH_{comp}(%), C_{comp,CO_2}(ppm), C_{comp,NH_3}(ppm) were equal to 24.2±0.3°C, 49.5±3%, 754±60 ppm and 7.43±2 ppm respectively. These values are lower than the ones obtained during nighttime, due to the higher supply fresh air.

Table 6. Comparison of: a) DPIEC supply flow rate and b) water consumption under localized and tunnel ventilation for a representative day during the summer season.

May						
Time	**Average outdoor**	**Average humidit**	**DPIE C +**	**DPIEC +**	**DPIEC + tunnel water**	**DPIEC + localized**

	temperature (℃)	y ratio (g/kg)	tunnel air supply flow rate (kg/s)	localized air supply flow rate (kg/s)	consumption (l/h)	water consumption (l/h)
0:00-4:00	13.63	9.74	0.15	0.12	0.00	0.00
4:00-7:00	12.08	8.85	0.11	0.09	0.00	0.00
7:00-10:00	19.65	10.47	0.20	0.17	0.07	0.06
10:00-11:00	28.35	10.23	0.30	0.25	0.38	0.30
11:00-13:00	33.33	11.29	0.44	0.35	8.31	6.65
13:00-16:00	35.68	11.51	0.52	0.42	10.41	8.33
16:00-18:00	31.80	11.68	0.50	0.40	8.33	6.66
18:00-19:00	27.60	11.57	0.45	0.36	5.76	4.61
19:00-21:00	18.10	8.17	0.26	0.21	1.52	1.22
21:00-0:00	12.68	7.78	0.16	0.14	0.03	0.02
June						
Time	**Average outdoor temperature (℃)**	**Average humidity ratio (g/kg)**	**DPIEC + tunnel air supply flow rate (kg/s)**	**DPIEC + localized air supply flow rate (kg/s)**	**DPIEC + tunnel water consumption (l/h)**	**DPIEC + localized water consumption (l/h)**
0:00-3:00	15.20	8.18	0.15	0.12	0.55	0.44
3:00-4:00	13.45	7.83	0.13	0.10	0.43	0.36
4:00-7:00	14.08	8.46	0.11	0.08	0.30	0.19
7:00-8:00	17.90	9.88	0.15	0.12	0.73	0.38
8:00-9:00	20.75	10.51	0.19	0.15	1.42	0.78
9:00-10:00	25.40	10.95	0.25	0.20	3.40	1.50
10:00-11:00	32.00	11.23	0.35	0.28	6.90	3.94
11:00-12:00	37.50	11.32	0.44	0.35	10.55	7.10
12:00-13:00	40.40	11.51	0.52	0.44	13.29	10.40
13:00-15:00	39.00	11.89	0.62	0.49	13.88	10.90
15:00-16:00	36.65	11.95	0.64	0.51	15.22	11.00
16:00	35.80	11.79	0.9	0.75	16.84	13.40
16:00-17:00	34.50	11.18	0.48	0.38	12.99	7.26
17:00-18:00	32.80	10.33	0.43	0.34	8.62	6.42
18:00-19:00	29.60	9.58	0.33	0.26	6.47	3.83
19:00-20:00	22.35	8.83	0.24	0.19	3.16	1.22
20:00-21:00	16.75	8.54	0.19	0.15	1.16	0.81
21:00-0:00	14.94	8.274	0.15	0.13	0.63	0.2
July						
Time	**Average outdoor temperature (℃)**	**Average humidity ratio (g/kg)**	**DPIEC + tunnel air**	**DPIEC + localized air**	**DPIEC + tunnel water consumption (l/h)**	**DPIEC + localized water**

			supply flow rate (kg/s)	supply flow rate (kg/s)		consumption (l/h)
0:00-4:00	17.52	9.39	0.19	0.14	1.21	1.04
4:00-7:00	16.58	9.58	0.16	0.12	0.75	0.60
7:00-8:00	20.60	10.25	0.20	0.15	1.01	0.81
8:00-9:00	27.30	10.45	0.28	0.18	2.42	1.94
9:00-10:00	35.25	10.13	0.31	0.22	4.95	3.96
11:00-12:00	35.60	10.87	0.46	0.26	10.60	6.16
12:00	38.40	12.05	0.57	0.48	12.00	10.29
12:00-13:00	42.95	11.18	0.53	0.37	11.70	9.62
13:00:18:00	40.12	8.99	0.41	0.31	10.43	8.30
18:00-19:00	33.50	8.50	0.36	0.30	7.65	6.06
19:00-21:00	25.60	8.82	0.31	0.26	6.13	4.99
21:00-0:00	20.48	9.02	0.25	0.18	2.88	2.44
August						
Time	**Average outdoor temperature (℃)**	**Average humidity ratio (g/kg)**	**DPIEC + tunnel air supply flow rate (kg/s)**	**DPIEC + localized air supply flow rate (kg/s)**	**DPIEC + tunnel water consumption (l/h)**	**DPIEC + localized water consumption (l/h)**
0:00-5:00	16.20	8.74	0.17	0.68	0.94	0.58
5:00-7:00	15.63	8.97	0.14	0.45	0.45	0.36
7:00-8:00	19.60	9.59	0.17	1.12	1.12	0.90
8:00-9:00	26.30	9.88	0.22	3.02	3.02	2.42
9:00-12:00	34.43	10.07	0.36	8.12	8.12	6.70
12:00	37.40	11.54	0.54	14.53	14.53	12.45
12:00-13:00	41.95	10.85	0.53	13.07	13.07	10.78
13:00-18:00	38.82	8.60	0.40	9.83	9.83	7.82
18:00-19:00	32.50	8.07	0.34	9.35	7.38	7.42
19:00-20:00	26.15	8.25	0.30	4.58	4.58	3.70
20:00-21:00	22.85	8.48	0.28	3.14	3.14	2.60
21:00-0:00	18.50	8.45	0.22	1.78	1.78	1.52
September						
Time	**Average outdoor temperature (℃)**	**Average humidity ratio (g/kg)**	**DPIEC + tunnel air supply flow rate (kg/s)**	**DPIEC + localized air supply flow rate (kg/s)**	**DPIEC + tunnel water consumption (l/h)**	**DPIEC + localized water consumption (l/h)**
0:00-4:00	15.22	8.19	0.14	0.12	0.56	0.49
4:00-7:00	14.78	8.79	0.13	0.10	0.33	0.27

7:00-8:00	17.90	9.88	0.17	0.14	0.73	0.58
8:00-9:00	20.75	10.51	0.22	0.18	1.42	1.14
9:00-10:00	25.05	10.99	0.30	0.24	3.26	2.61
11:00-12:00	36.80	11.51	0.51	0.42	10.80	9.02
12:00	39.00	12.18	0.60	0.51	13.36	11.45
12:00-13:00	39.70	9.77	0.46	0.38	11.19	9.27
13:00:18:00	35.70	8.68	0.37	0.29	8.63	6.87
18:00-19:00	28.90	8.71	0.33	0.26	5.79	4.59
19:00-21:00	19.63	8.65	0.25	0.20	2.19	1.76
21:00-0:00	14.68	8.44	0.18	0.15	0.68	0.58

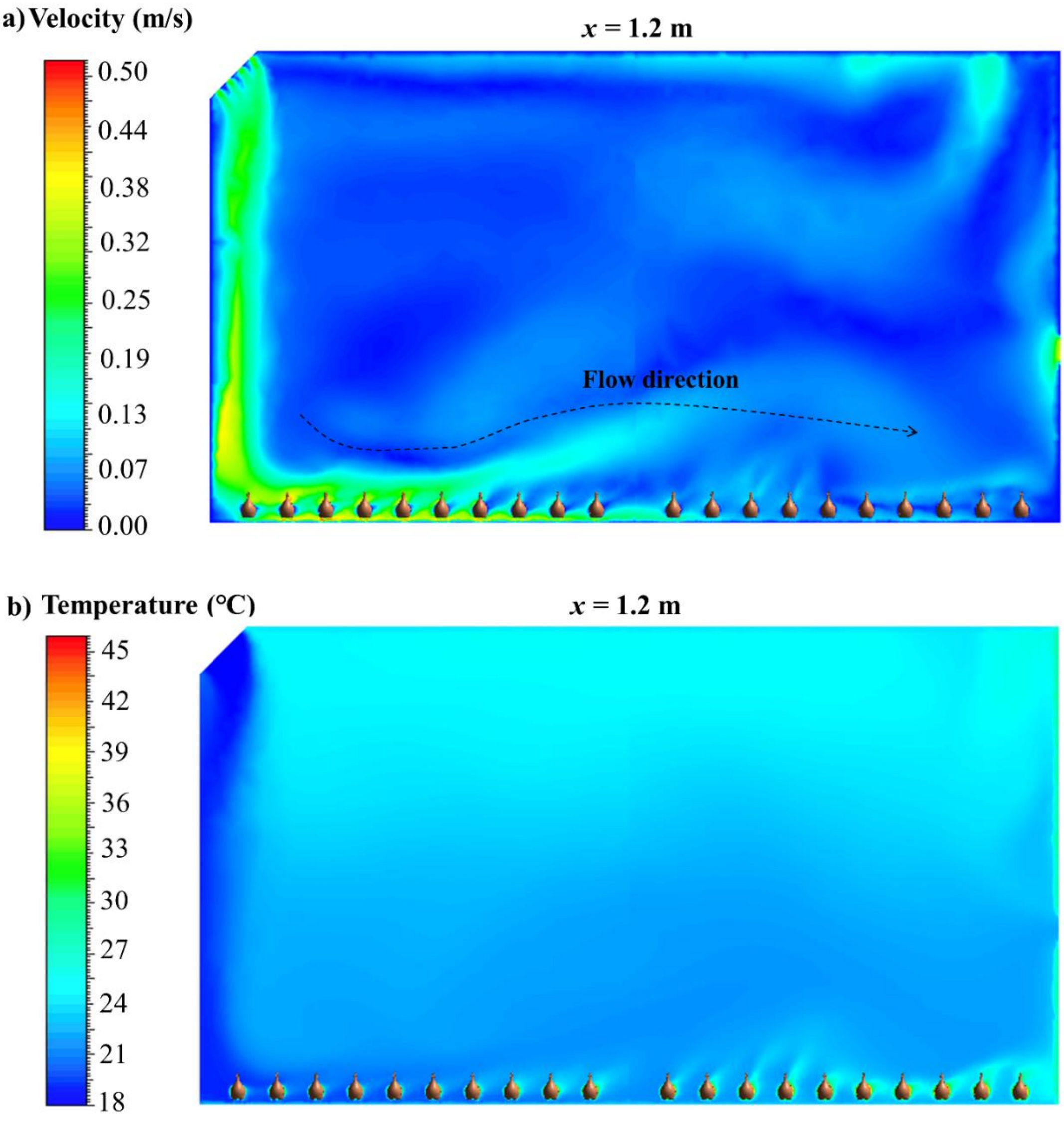

Fig. 11. Illustration of the: a) velocity and b) temperature contours at x = 1.2 m plane.

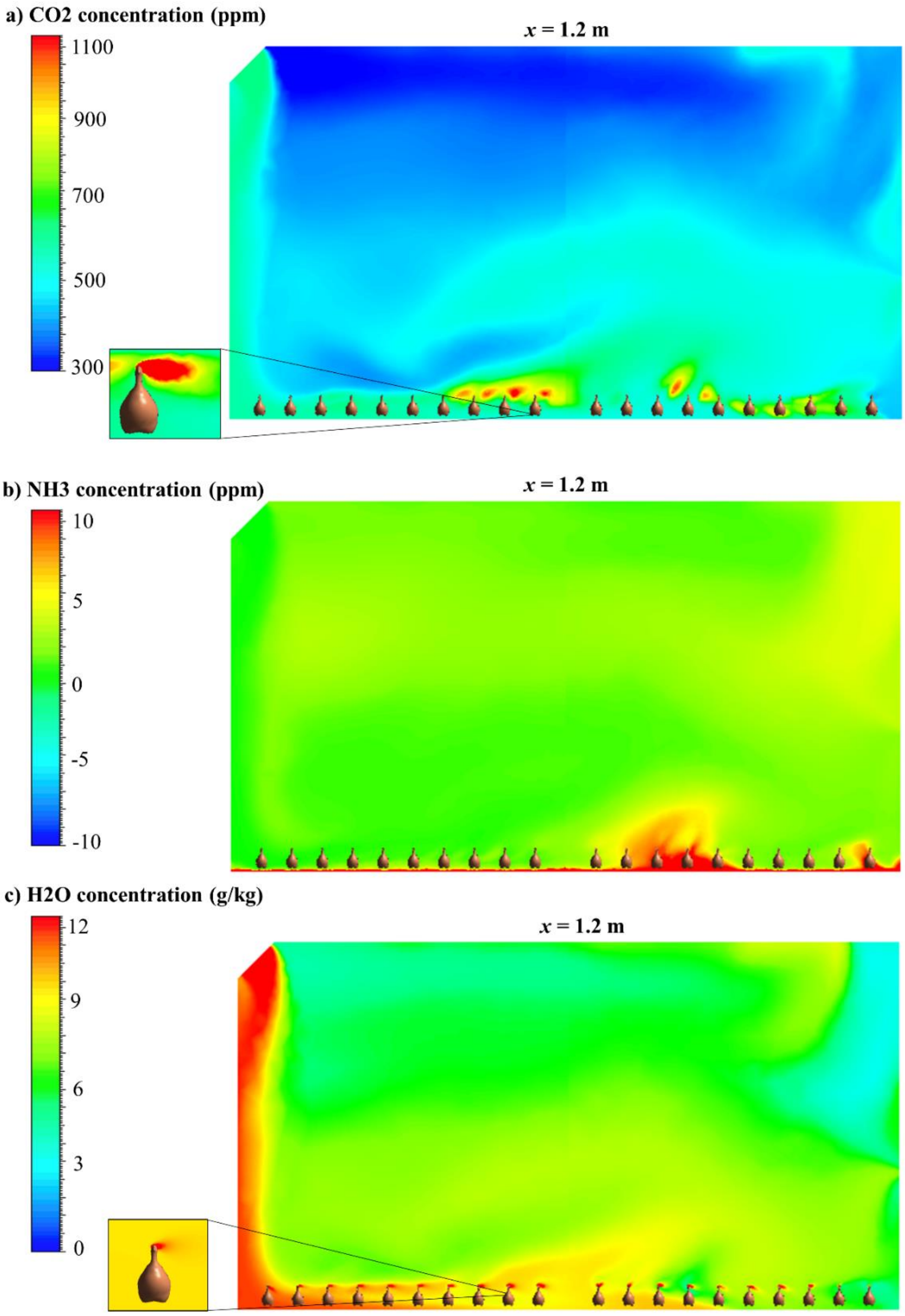

Fig. 12. Illustration of: a) the CO_2 concentration (ppm), b) the NH_3 concentration (ppm), c) the specific humidity (g/kg) at the x = 1.2 m plane with close ups of the hens' of the respiratory flow emissions.

The effect of localized air distribution can be seen more clearly in **Fig. 11** and **12**, which illustrate the contours of velocity, temperature, CO_2, NH_3 and specific humidity ratio concentrations in the *x* = 1.2 m plane for the month of May. According to **Fig. 11**, the supplied fresh air drops downwards due to buoyancy effects and spreads in the hen-occupied zone conditioning and cleaning it from contaminants by blowing at the respiratory flows from the hens and diffusive flux from the floor. Note that the pen on the left-hand side has lower temperatures and lower contaminants' concentrations than the pen on the right. This is since it is directly located beneath the supply diffuser. Note that velocities in the hen-occupied zone ranged between 0.1 – 0.4 m/s, which is acceptable in poultry houses.

6.4 Economic analysis

To confirm the advantage of DPIEC + tunnel ventilation over the DEC + tunnel ventilation and the advantage of using DPIEC with localized ventilation rather than tunnel ventilation, an economic feasibility study was conducted for the three systems. For this reason, the life cycle cost (LCC) including initial investment and yearly costs of the three passive systems were computed based on equation (6):

$$LCC = I_0 + \sum_{i=1}^{N} \frac{C_i}{(1+a)^i} - \frac{C_N}{(1+a)^N} \tag{9}$$

where I_0 is the initial investment (year 0) made for each system ($), including the investment and installation cost of the DEC (1760$ ×8 units for 8 compartments), the DPIEC (1850 $ ×8 units). The yearly costs C_i (*i* denotes the year index and *N* is the number of years or system holding period = 50 years in this case) for the three systems include the electric power consumption (KWh) of the fans that supply and exhaust fresh air to and from the poultry house and pumps that supply water to the DEC/DPIEC units. The latter was multiplied by the electricity tariff in Lebanon (0.13$/KWh) to obtain the yearly electric costs of the three systems. The yearly electric costs were equal to 826$, 668$ and 540$ for the DEC + tunnel, DPIEC + tunnel and DPIEC + localized respectively. Note that the change in local currency value over the holding period was accounted for using the discount rate a, which varies between 0 to 10%. A typical value of 5 % was considered in this study [46]. C_N is the salvage cost of the systems ($) after 50 years, which needs to be deducted from the LCC. Its value is taken such that the depreciation rate of the systems does not exceed 90% at the end of its useful period of operation [47]. **Figure 13** illustrates the yearly variation of the LCC ($) for the three systems. According to **Fig. 13**, for the first 5 years and 3 years of using the DEC + tunnel system, the latter had lower LCC (and hence was more economically profitable) than the DPIEC + tunnel and DPIEC + localized respectively. After these years, the DEC + tunnel ventilation was no longer profitable throughout the holding period. Thus, using DPIEC systems will be more economically beneficial on top of better performance in meeting the poultry house cooling and IAQ needs throughout the summer season. Between DPIEC + tunnel ventilation and DPIEC + localized ventilation systems, the localized air distribution would be more economically beneficial (LCC was 10% cheaper) while providing similar indoor conditions (temperature and IAQ) in the poultry house.

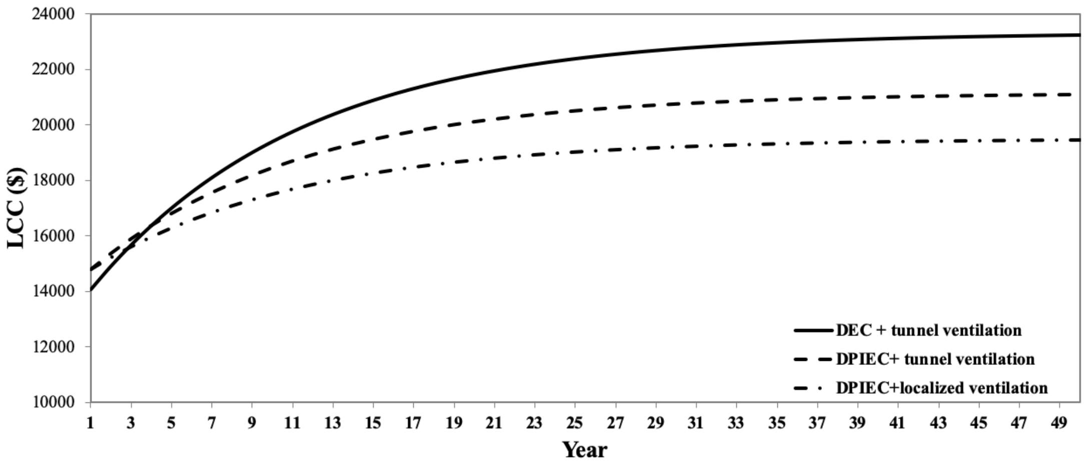

Fig. 13. Comparison of the LCC yearly variation for the DEC + tunnel ventilation, DPIECs + tunnel ventilation and DPIEC + localized ventilation systems.

CHAPTER 7

CONCLUSION

In this work, the power consumption of three passive ventilation systems were compared in terms of their ability to meet temperature and IAQ requirements in a poultry house located in Beqaa Valley, Lebanon. The first two systems to be compared consist of either a DEC or DPIEC systems coupled with a conventional tunnel ventilation system. The third system was a DPIEC coupled with a localized air distribution system for further reduction in power consumption. A modular analysis was adopted, where each poultry house compartment consisting of two pens was considered. Mathematical models were developed for the DEC/DPIEC systems and the compartment conditioned by the conventional tunnel ventilation as homogeneous conditions of temperature and IAQ were considered. As for the compartment space model conditioned by the localized system, 3D CFD modeling was adopted. The compartment space model was used to size the DEC/DPIEC units for peak load removal found during the month of July. The hourly variation of the air + water supply were then computed for the two systems. A similar analysis was conducted for the CFD model to determine further reduction in fresh air intake and water consumption. Simulation results and a simple economic analysis showed that the DPIEC systems under conventional ventilation were more economically beneficial (4.3%) than the DEC systems, while achieving better thermal environment and IAQ. On the other hand, using localized ventilation instead of conventional tunnel ventilation was 10% more economically beneficial, while achieving similar conditions of temperature and IAQ.

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